Gravitational waves meet effective field theories, Benasque, Spain

August 21, 2023

Contents

About

General Relativity (GR) describes gravity on a huge range of scales, field strengths and velocities. However, despite its successes, GR has been showing its age. Cosmological data support the existence of Dark Sector, but may also be interpreted as a breakdown of our understanding of gravity. Also, GR is intrinsically incompatible with quantum field theory, and should be replaced, at high energies, by a (still unknown) quantum theory of gravity. This deadlock may prelude to a paradigm change in our understanding of gravity, possibly triggered by the direct observations of neutron stars and black holes by gravitational-wave interferometers. The recent LIGO/ Virgo observations have already made a huge impact on our theoretical understanding of gravity, by severely constraining several extensions of GR. In this workshop, we will focus on effective field theories of gravity extending/modifying GR, focusing on their predictions for the generation and propagation of gravitational waves, and on their comparison with experiments. Our goal is to establish new synergies among different communities, including numerical relativity, post-Newtonian theory, data analysis and cosmology.

Organizing committee

Enrico Barausse Laura Bernard Miguel Bezares

Timetable

Monday, 21 of August.

08:45–09:15	**Registration**		
9:15–09:30	**Welcome**		
09:30–10:30	IS	**Cliff Burgess**	The Gravity of Light Scalars (Naturally)
10:30–11:00	**Coffee**		
11:00–12:00	IS	**Antonio Padilla**	The cosmological constant is probably still zero
12:00–13:00	IS	**Mariana Carrillo**	Testing EFTs: amplitudes, gravitational waves, and causality
13:00–15:00	**Lunch**		
15:00–16:00	IS	**Eugeny Babichev**	Black holes in scalar-tensor theories
19:00–22:00	**Welcome reception**		

Tuesday, 22 of August

09:30–10:30	IS	**Tessa Baker**	Sirens & Structures: beyond-GR effects in cosmology
10:30–11:00	**Coffee**		
11:00–12:00	IS	**Johannes Noller**	Testing gravity on all scales
12:00–13:00	IS	**Filippo Vernizzi**	Gravitational two-body scattering and angular momentum balance
13:00–15:00	**Lunch**		
15:00–16:00	IS	**Alessandra Silvestri**	Large Scale Structure and Dark Energy: theoretical challenges and progress

IS: Invited Speaker
$*$: TBC

Wednesday, 23 of August

09:30–10:30	IS	**Andrea Maselli**	Fundamental fields, asymmetric binaries, and LISA observations within a self- force approach
10:30–11:00	**Coffee**		
11:00–12:00	IS	**Félix-Louis Julié**	Compact binary systems in modified gravity theories and their effective-one-body description
12:00–13:00	IS	**Marco Crisostomi**	Gravitational wave generation in dark energy effective field theories
13:00–15:00	**Lunch**		
15:00–15:20	IS	**Feng-Li Lin**	Subleading double soft graviton dressing and its G^2 waveform contribution
15:20–16:20	IS	**Discussion session**	Alessandra Silvestri & Johannes Noller

Thursday, 24 of August

09:30–10:30	IS	**Aron Kovacs**	On the Cauchy problem in effective theories of gravity
10:30–11:00	**Coffee**		
11:00–12:00	IS	**Luis Lehner**	Addressing the intrinsic tension between EFT gravity theories and the EOMs they yield
12:00–13:00	IS	**Aaron Held**	Numerical Relativity in EFTs of Gravity
13:00–15:00	**Lunch**		
15:00–16:00	IS	**Pau Figueras**	Simulating higher derivative theories of gravity

Friday, 25 of August

09:30–10:30	IS	**Harald Pfeiffer**	Recent progress in the simulations of binary black holes
10:30–11:00	**Coffee**		
11:00–12:00	IS	**Maxence Corman**	Nonlinear dynamics of compact object mergers in Einstein-scalar-Gauss-Bonnet gravity
12:00–13:00	IS	**Discussion session**	Marco Crisostomi & Luis Lenher
13:00–15:00	**Lunch**		
15:00–16:00	IS	**Dina Traykova**	Exploring scalar field models of the dark sector near compact objects

IS: Invited Speaker
$*$: TBC

List of Abstracts – Talks

Monday 21th

The Gravity of Light Scalars (Naturally)

Cliff Burguess

McMaster University, Hamilton, Canada

We live in remarkable times: the recent advent of gravitational-wave physics allows us to test gravity in a strongly relativistic regime. We also have plausible examples of UV physics that can reconcile General Relativity with Quantum Mechanics. But there is also Bad News: although Decoupling - which beautifully explains why low-energy measurements are largely insensitive to UV details - seems a central organizing feature of Nature, it also seems to thwart the extraction fundamental insights about UV modifications to gravity from astrophysical or cosmological observations. This talk argues that all is not lost because some UV features can robustly penetrate the decoupling barrier. In particular all known UV completions contain accidental symmetries that robustly point to the existence of scalars in the low-energy effective theory (and these are not just axions). Normally we are taught that naturalness arguments preclude these scalars from being light enough - or, like axions, if light are too weakly coupled - to be important to tests of gravity. I argue that any natural explanation of the small size of the observed Dark Energy necessarily puts us in a regime where some scalars are dilatons (ie are naturally light and have Brans-Dicke couplings to matter). The question of why these scalars are not already detected motivates more detailed studies of how such naturally light scalars can interact with bulk matter, and whether screening mechanisms exist that could have hidden them from present-day tests of gravity. Crucially they must do so in a way consistent with other properties of UV completions of gravity (in a way that standard screening mechanisms - like Chameleons - are not). In this talk I describe new proposals for such UV-consistent screening mechanisms and explore some of the implications they might have for tests of gravity and their possible relevance to other problems (like the Hubble tension) we see in the world around us.

The cosmological constant is probably still zero

Antonio Padilla

University of Nottingham, Nottingham, UK

We consider a wide class of four-dimensional effective field theories in which gravity is coupled to multiple four-forms and their dual scalar fields, with membrane sources charged under the corresponding three-form potentials. Four-form flux, quantised in units of the membrane charges, generically generates a landscape of vacua with a range of values for the cosmological constant that is scanned through membrane nucleation. We list various ways in which the landscape can be made sufficiently dense to be compatible with observations of the current vacuum without running into the empty universe problem. Further, we establish the general criteria required to ensure the absolute stability of the Minkowski vacuum under membrane nucleation and the longevity of those vacua that are parametrically close by. This selects the current vacuum on probabilistic grounds and can even be applied in the classic model of Bousso and Polchinski, albeit with some mild violation of the membrane weak gravity conjecture. We note that there are other models where the membrane weak gravity conjecture is not violated but where the same probabilistic methods can be used to tackle the cosmological constant problem.

Testing EFTs: amplitudes, gravitational waves, and causality

Mariana Carrillo

Imperial College, London, U.K

In this talk, I will review different approaches to testing Effective Field Theories (EFTs). First, I will briefly review how amplitude techniques can allow us to extract classical observables during the merge of a black hole binary for generic EFTs of gravity including minimal and non-minimal couplings. In the second half of my talk, I will focus on how to obtain bounds on Wilson coefficients of EFTs from the requirement of physical principles. I will compare the strength of positivity and causality bounds and show how applying both can be a powerful tool. Both of these techniques allow us to test EFTs effectively when comparing theoretical predictions to observations.

Black holes in scalar-tensor theories

Eugeny Babichev

Universite Paris-Saclay, Orsay, France

I will review black holes in scalar-tensor theories. One class of theories which allows analytic construction of solutions is related to shift-symmetric and parity-preserving scalar field. The shift symmetry of the scalar field yields a Noether conserved current which proves extremely useful for integrating the equations of motion. Another type of symmetry is the conformal invariance of the equation of motion of the scalar field that allows to integrate equations of motion analytically in particular classes of theories. Finally, I will consider conformal and disformal transformations as a tool to obtain new non-trivial solutions in DHOST theories.

Tuesday 22th

Sirens & Structures: beyond-GR effects in cosmology

Tessa Baker

Queen Mary University of London, London, United Kingdom

I'll talk about a number of ways deviations from GR may show up in cosmological observables, and some of the latest techniques for constraining these effects. Starting with gravitational wave propagation, we'll talk about the remaining possibilities for testing deviations of the GW propagation speed post-GW170817. I'll also explain the dark sirens method, and how it can be used to constrain deviations from GR even in the absence of EM counterparts to GW events. Finally, we'll discuss the current frontier for performing simulations of large-scale structure in modified gravity theories, readying ourselves for the upcoming galaxy clustering data from surveys like DESI, Euclid, and LSST.

Testing gravity on all scales

Johannes Noller

University of Portsmouth, Portsmouth, U.K.

Recent years have seen great progress in probing gravitational physics on a vast range of scales, from the very largest cosmological scales to those associated with high energy particle physics. Combining insights and constraints from systems probing such drastically different scales naturally presents several challenges and I will discuss how effective field theory methods are a particularly powerful tool in identifying these challenges while also providing novel insights into the underlying physics. Focusing on the speed of gravitational waves as a guiding observable, I will more specifically discuss how we can put together information from constraints (and forecasts) for Ligo-Virgo-Kagra and LISA, from binary pulsars, from large scale structure surveys, as well as from novel theoretical constraints on gravitational interactions (especially so-called 'positivity' bounds).

Gravitational two-body scattering and angular momentum balance

Filippo Vernizzi

Institut de Physique Théorique, Université Paris-Saclay, France

Recently, there has been significant activity in applying the so-called post-Minkowskian expansion (i.e., the perturbative expansion in powers of Newton's constant G while encompassing all orders in velocity) to the relativistic two-body problem. Within this framework, I will review the computation of gravitational radiation released during the scattering of two bodies at the leading order in G. Additionally, I will derive a new balance law for the angular momentum emitted in gravitational two-body scattering. This will address some puzzles related to the well-known supertranslation-dependence of angular momentum at future null infinity

Large Scale Structure and Dark Energy: theoretical challenges and progress

Alessandra Silvestri

Leiden University, Leiden, Netherlands

I will focus on the challenge posed by dark energy and discuss theoretical issues involved in finding an optimal framework to unveil its nature from upcoming high precision measurements of the large scale structure, giving an overview of recent progress. I will discuss the role of theoretical priors based on effective field theory methods, and the complementary role of gravitational waves.

Wednesday 23th

Fundamental fields, asymmetric binaries, and LISA observations within a self-force approach

Andrea Maselli

Gran Sasso Science Institute (GSSI), L'Aquila, Italy

In this talk I will discuss in which cases black holes carry a scalar charge, and the implications for models in which the latter scales with the black hole mass. I will talk about the phenomenological implications of these insights for the physics of compact systems, and how asymmetric binaries are ideal sources for searches of new fundamental scalars. I will lay out the framework for modelling such binaries in an effective field theory approach, and present some first forecasts on LISA's ability to constrain the feature of the scalar fields from future observations.

Compact binary systems in modified gravity theories and their effective-one-body description

Félix-Louis Julié

Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam, Germany

Gravitational wave astronomy finally allows us to test observational signatures of modified gravity theories in the dynamical, strong-field regime of a coalescing compact binary system. I will show how to derive analytic gravitational waveforms associated to the coalescence of a "hairy" black hole binary, focusing on the example of Einstein-scalar-Gauss-Bonnet gravity (ESGB). I will present the post-Newtonian (PN) Lagrangian and gravitational wave fluxes. I will then extend the scope of the PN approximation to the strong-field regime near merger by building an effective-one-body (EOB) Hamiltonian at 3PN. The PN framework relies on describing compact bodies as point particles with scalar-field-dependent masses. I will show how to compute and interpret the latter for an ESGB black hole, in light of the first law of black hole thermodynamics.

Gravitational wave generation in dark energy effective field theories

Marco Crisostomi

SISSA, Trieste, Italy and INFN Sezione di Trieste

One of the challenges in describing dark energy as a dynamical field is that we do not see any sign of it in local tests of gravity. Moreover, all gravitational wave events detected so far are in very good agreement with General Relativity predictions. In this talk I will discuss about kinetic screening as a way to overcome this dichotomy and I will present our recent results in testing it with black hole collapse, and the late inspiral and merger of binary neutron stars.

Subleading double soft graviton dressing and its G^2 waveform contribution

Feng-Li Lin

Department of Physics, National Taiwan Normal University, Taiwan

Following a recent proposal to describe inelastic eikonal scattering processes in terms of gravitationally dressed elastic eikonal amplitudes, we motivate a double graviton dressing and investigate its properties. This is derived from the known Wilson line operator up to sub-eikonal corrections in the worldline formalism for gravitationally interacting theories. The dressing involves a product of terms – a coherent piece with contributions to all orders in the gravitational coupling constant, and an exponential factor quadratic in graviton modes. We use this dressing to derive a tail term in the order G^2 waveform from a soft limit of the double graviton emission.

Thursday 24th

On the Cauchy problem in effective theories of gravity

Aron Kovacs

SISSA, Trieste, Italy and INFN Sezione di Triest

Effective field theory (EFT) provides a way of parameterizing strong-field deviations from General Relativity that might be observable in the gravitational waves emitted in a black hole merger. To perform numerical simulations of black hole mergers in an EFT it is necessary that theory that admits a well-posed initial value formulation. In the first part of my talk, I will review recent results on the initial value formulation of gravitational EFTs (beyond General Relativity) with second order equations of motion. In the second part, I will discuss some ideas to deal with EFTs with higher derivative equations. In particular, I will present a new well-posedness result for a class of Horava-Lifshitz theories of gravity.

Addressing the intrinsic tension between EFT gravity theories and the EOMs they yield

Luis Lenher

Perimeter Institute for Theoretical Physics, Waterloo, Canada

The use of EFT for constructing extensions to General Relativity comes with a 'catch': the EOMs they define, typically contain characteristics which are in tension with standard mathematical tools to analyze their behavior and attempt to solve them. In this talk I will discuss the issue and a strategy to deal with them together with some general lessons for potential data analysis.

Numerical Relativity in EFTs of Gravity

Aaron Held

Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universit at Jena, Jena, Germany

To set the stage, I discuss the interplay of physical and fiducial degrees of freedom, field redefinitions, ghost instabilities, and high-energy behaviour in effective field theories (EFTs) of gravity. In the main part of the talk, I then present an approach to achieve well-posed numerical evolution in said theories. This approach is based on (i) identifying the nonlinear degrees of freedom (both physical and fiducial) and (ii) employing order-reduction methods to recast the respective evolution system. I exemplify the above methodology for a complete set of quadratic curvature corrections to GR (henceforth Quadratic Gravity), for which it can be proven that the approach leads to a quasilinear, hence, due to a theorem by Leray, well-posed evolution system. The resulting stable numerical evolution scheme grants novel access to (i) the physical stability of the Ricci-flat subsector, i.e., of the GR vacuum, (ii) the nonlinear endpoint of a well-established linear instability, and (iii) the fully nonlinear evolution of binary systems. I end with an outlook on how to generalize the approach to wider classes of gravitational theories. The talk is based on: 2306.04725 (with Hyun Lim), 2209.01867 (with Jun Zhang), 2104.04010 (with Hyun Lim).

Simulating higher derivative theories of gravity

Pau Figueras

School of Mathematical Sciences, Queen Mary University of London, London, United Kingdom

TBA

Friday 25th

Recent progress in the simulations of binary black holes

Harald Pfeiffer

Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam, Germany

Solutions of the two-body problem in general relativity (GR) are an essential part of studying alternative theories. For one, techniques developed in GR provide the foundations for solutions in alternative theories of gravity. Moreover, all possible solutions within GR must be known —and must be known at sufficiently high accuracy— in order to confidently interpret future gravitational wave results: Is an assumed deviation from GR really caused by a failure of GR to represent the source, or is one merely misinterpreting modeling errors or missing physical effects as a deviation? This talk summaries recent progress in the numerical modeling of binary black holes within the SXS collaboration. Particular emphasis will be placed on eccentric binaries, and on new methods to address binaries at large mass-ratios.

Nonlinear dynamics of compact object mergers in Einstein-scalar-Gauss-Bonnet gravity

Maxence Corman

Perimeter Institute for Theoretical Physics, Waterloo, Canada

In recent years, gravitational wave observations of compact objects have furnished new opportunities to test our understanding of gravity in the strong field, highly dynamical regime. In order to perform model dependent tests of General Relativity with these observations one needs accurate inspiral-merger-ringdown waveforms in alternative theories of gravity. In this talk, we will discuss progress but also the challenges in numerically solving for the dynamics of compact object mergers in a class of modified theories of gravity. The theory we focus on is Einstein-Scalar-Gauss-Bonnet gravity, motivated by effective field theory but also admitting scalar hairy black hole solutions.

Exploring scalar field models of the dark sector near compact objects

Dina Traykova

Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam, Germany

Despite the numerous observational evidence for the existence of dark matter and dark energy, their exact origin and properties remain largely unknown. The standard cosmological model, known as -Cold Dark Matter, has so far been the most successful explanation of current observations. However, due to some unresolved inconsistencies and tensions, many alternatives have been explored in recent years, including an additional solar field minimally or non-minimally coupled to gravity. In this talk I will outline the main properties and characteristics of some such models and how we can use gravitational wave observations in the search of dark matter or dark energy signatures. I will also comment on some of the issues we encounter in numerically studying the effect these fields have on compact object binaries and any implications for possible future detections.